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## Abstract

A number of grid-generation and CFD-process software tools have been developed which greatly improve the ability to perform overset CFD analysis of complex configurations. These tools have been applied to the task of generating grids and computing the flow field about two different high-lift aircraft configured for landing: a Boeing 777-200, and a High-Wing Transport with externally blown flaps. The high-lift flow-fields of both aircraft were simulated using the OVERFLOW solver. A Navier-Stokes simulation of a complete Boeing 777-200 aircraft configured for landing was obtained in less than 50 labor days with a lift coefficient which differs from experimental data by only 1.2%. This is an order of magnitude reduction in the cycle time for the entire computational process compared to a similar high-lift simulation effort that took place two years earlier. The new software was utilized to perform a flow-field analysis of a flap-rigging modification for the Boeing 777-200 aircraft in only four days. The software was also utilized to simplify

grid generation of the High-Wing Transport for many different geometric configurations. The reductions in computational cycle time are primarily the result of the use of an automatic script system that streamlines the overset grid preparation process. Analysis of the process shows that over-setting the the grid system is now the most labor-intensive part of a single-point analysis; however, for multi-point analyses, multiple viscous flow-solver runs are costly.

## Introduction

Calculating the viscous fluid flow over a high-lift system of a subsonic commercial aircraft is one of the most difficult problems in Computational Fluid Dynamics (CFD). Even in two-dimensions (2D), state-of-the-art CFD codes fail to consistently predict, with sufficient accuracy, trends with Reynolds number or trends with flap/slat rigging changes.<sup>1</sup> High-lift flow-field analysis is also a very important problem for commercial aircraft companies; the payoffs for understanding it and designing a more efficient high-lift system for commercial jet transports are quite high.<sup>2</sup> Increases in lift coefficient and in lift-over-drag can lead to a simpler high-lift system, resulting in less weight and less noise, as well as increases in both payload and range.

The difficulties in simulating high-lift flows come from the severe complexity of both the geometry and the flow field. The complexity of the flow field stems from the wing having multi-elements with very small

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gaps between them, leading to an interaction of various viscous flow phenomena. As stated by Meredith,<sup>2</sup> these flow phenomena include boundary-layer transition, shock and boundary-layer interactions, viscous wake interactions, confluent wakes and boundary layers, and separated flows. Since the fluid dynamics is dominated by viscous effects, only a high-fidelity simulation using the Navier-Stokes equations can provide the accuracy necessary to assist in aircraft design.

The stated goal of the High-Lift Sub-element within the NASA Advanced Subsonic Technology/Integrated Wing Design (AST/IWD) Program is the development and validation of an improved three-dimensional high-lift design methodology. In particular, it is desired to incorporate modern Navier-Stokes techniques into the current high-lift design process in order to ultimately decrease overall design-cycle time. During the period from December 1995 through May 1996, an applied CFD research team, comprised of members from NASA, Boeing and the former McDonnell Douglas prepared a white paper<sup>3</sup> whose intent was to further define the role of CFD in achieving this goal. The team found that the CFD capability in 1995 required significant improvements in order to meet the program goal in a timely fashion. Various problem issues related to CFD analysis of high-lift configurations were stated, including: predictive accuracy of three-dimensional Navier-Stokes methods for high-lift flows could not be readily assessed; there was a lack of sufficient three-dimensional experimental data necessary to calibrate CFD codes on high-lift configurations; at the time there were only a limited number of three-dimensional high-lift simulations that had been conducted; such CFD simulations require a significant amount of computational resources to model the complex geometries and flow physics; and the complexity of the geometry for even a simplified three-dimensional high-lift configuration presents an immense challenge. Thus it was recognized that it would be difficult to accomplish all the desired applied CFD tasks within the AST/IWD Program without significant CFD tool development.

According to the white paper,<sup>3</sup> in order for Navier-Stokes analyses to play a significant role in the design process, CFD technology must be matured to the point where designs can go from CAD definition to final Navier-Stokes analysis in one week, with minor changes of the geometry being computed on the order of one to two days. An intermediate goal along the path of this strategic vision which could be met within the time frame of the AST/IWD Program was set forth within this paper: "Decrease the time required to go from CAD to final post-processed solution for a complex three-dimensional high-lift geometry from hundreds of days to 50 days. A second solution for minor perturbations should be achieved within five days."

The current paper describes the overset CFD tool development that was performed as part of the NASA AST/IWD Program in order to meet the 50-day and 5-day goals. The following sections present: motivation for the choice of the overset CFD approach; some previously computed high-lift CFD benchmarks; the new software tools developed for this effort; computation of the flow about a complete Boeing 777 high-lift aircraft in 48 working days; an analysis of the CFD process time required to perform the 777 analysis; the analysis of a new 777 flap in four working days; and application of the new software to the analysis of a High Wing Transport (HWT) high-lift aircraft. These results will show that the new overset CFD tools have dramatically decreased the CFD process time, and that the 50-day and 5-day goals were met.

### Overset CFD Approach

Efforts to build an automated CFD capability for three-dimensional (3D) high-lift problems are necessarily limited because of the extensive resources required by such a problem. Some 3D CFD results for simple high-lift configurations have been reported by Mathias *et al.*,<sup>4,5</sup> by Jones *et al.*,<sup>6</sup> and by Nash and Rogers.<sup>7</sup> Other complex configurations which are more representative of a high-lift aircraft have been reported previously by two of the current authors<sup>8,9</sup> and by Mavriplis.<sup>10,11</sup> In Refs. 8 and 9, work utilizing an overset, or chimera<sup>12</sup> grid approach to the flow over a Boeing 747PD high-lift configuration was presented. In this work, the overset approach proved to be well suited for dealing with the complex geometry, and provided what appeared to be accurate solutions. A detailed assessment of the accuracy was not possible due to significant differences between the computational and experimental geometries, and the fact that only limited experimental results were available. A drawback of the overset approach was the significant amount of user input and time required to assemble the complex grid system for this high-lift geometry. The work of Mavriplis<sup>10,11</sup> was done utilizing an unstructured grid approach. This approach offers an alternative which provides automated grid-generation, however it is still under development. Among other issues, it does not provide a capability for resolving off-body shear-layers and wakes.

The overset grid method has been utilized in the current work. This method was chosen for several reasons. Because of the arbitrary overlapping allowed between neighboring grids, the volume-grid generation is much simpler than if all grids were required to be point-wise continuous at their interfaces, as is required by a multi-block-grid approach. The overset volume-grid generation can be accomplished using a hyperbolic or marching grid-scheme, instead of an elliptic-based solver. This results in grids that tend to be more orthogonal and have smoother changes in grid spacing.

**Table 1 Aircraft Components Included in the Subsonic Transport CFD Models**

Aircraft Component	Simplified HWT	HWT	Boeing 747PD	Boeing 777-200
Body	Fuselage	Fuselage	Fuselage	Fuselage
Main Wing	Wing Wing Tip	Wing Winglet	Wing Wing Tip	Wing Wing Tip
Leading-Edge Devices	Full-span Slat	Inboard Slat Mid Slat Outboard Slat	Full-span VCK	Inboard Slat Krueger Outboard Slat
Trailing-Edge Devices	Vane Flap	Vane Flap 4 Hinge Fairings	Inboard Flap Flaperon Outboard Flap	Inboard Main Flap Inboard Aft Flap Flaperon Outboard Flap 3 Flap Fairings
Engine/Nacelle	2 Nacelles 2 Core Cowl	2 Nacelles 2 Core Cowl 4 Nacelle Strakes		1 Nacelle 1 Core Cowl
Strut/Pylon		2 Pylons		1 Strut
Tail				Vertical Tail
Total Points	16 million	33.2 million	8.9 million	22.4 million

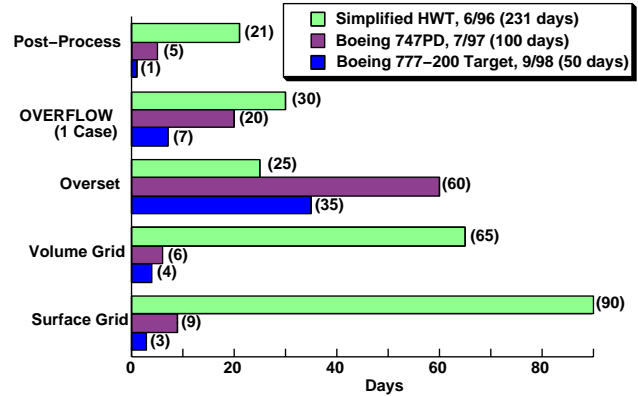
The authors' experience with overset grids<sup>7,8,9,13,14</sup> as well as the experience of others<sup>15</sup> has shown that the overset approach is amenable to automation.

Finally, an advantage of using the overset grid approach is that the flow can be computed with the OVERFLOW<sup>16,17</sup> flow solver. This code is written to be efficient for computing very large-scale CFD problems on a wide range of supercomputer architectures. On vector supercomputers with very fast secondary memory devices, the OVERFLOW code includes an out-of-core memory management option, such that the total memory used is a function of the largest zone in the grid system, not the total number of grid points. The code is efficiently vectorized, and its multi-tasking directives take advantage of multiple processors. For cache-based multiple-processor machines, the code has been parallelized using both a shared memory algorithm, and with a Message-Passing Interface (MPI) library for non-shared memory systems. See the works of Jespersen<sup>18</sup> and Taft<sup>19</sup> for more details.

#### CFD Process Time Benchmarks

In order to provide a baseline for measuring improvements, the overset CFD process was evaluated for two previous computations of subsonic transports configured for high lift: a High Wing Transport and a Boeing 747PD. Both of these applications were performed by the current authors under the AST/IWD Program. The first application of overset grids to a realistic subsonic transport configured for high lift was a simplified model of a HWT. Work on this analysis

started in late December 1995 and simulation results were obtained in May 1996. The geometry for this version of a HWT included the fuselage, a full-span slat, the main wing with a rounded tip, a vane/flap combination and inboard and outboard nacelles; these components are listed in Table 1.



**Fig. 1 Comparison of CFD process times.**

Approximate completion times for each CFD task are shown in Fig. 1 for the simplified HWT and the 747PD, where time is reported in units of days, where one day is equivalent to one eight-hour labor day. The third set of numbers included in Fig. 1 are the target times that were forecast as being necessary for the CFD process in order to meet the 50-day goal. The 1996 HWT benchmark for total CFD cycle time is about 231 days. The CAD definition to surface definition step for the HWT required 45 days; this step

is not shown in Fig. 1. This was a time consuming process in the case of the HWT because the only geometry definition available was a manufacturing CAD database; this required a lot of CAD manipulation to produce the external aerodynamic surfaces.

A geometrically complete model of the HWT was developed and simulated in the period from September 1996 through March 1997. The components included on this model are shown in Table 1. A total of 33.2 million points within 153 zones were required to discretize this geometry. Significant amounts of software and tool development time were spent while building the grid system, particularly in the pylon/nacelle area. While efforts were focused on development, the CFD process times were not monitored. Therefore, the complete model of the HWT is not established here as one of the CFD process baseline cases, and is not included in the comparison shown in Fig. 1.

The second baseline application, a Boeing 747PD configuration, was simulated in 1997. This high-lift configuration was modeled without any engines. Because the HWT model was the first transport configuration to be simulated, a large amount of time was required to design usable grid topologies for the wing elements. The Boeing 747PD application utilized these grid topology strategies and consequently realized a significant reduction in surface and volume grid generation time, decreasing from 155 to 15 days. On the other hand, the time required to overset the grid system more than doubled; this increase is due to the added geometric complexity of the flap system for the Boeing 747PD configuration. The model geometry included the fuselage, the main wing, a full-span Variable-Camber Krueger (VCK), inboard and outboard flaps, and a flaperon, as listed in Table 1. The gaps between elements were often smaller than on the HWT and some of the elements such as the flap/flaperon were sealed; these small gaps and seals introduced significant new difficulties for the overset process.

The wall-clock time to complete one OVERFLOW simulation on the resulting grid system was less than 3 weeks for the Boeing 747PD application. This reduction in time was due in part to a better quality initial grid system which required less user intervention during convergence, and because it was a smaller grid system (8.9 million points versus 16 million points for the simplified HWT). Furthermore, the newly introduced multi-grid option<sup>17</sup> in OVERFLOW was used to increase the convergence rate of the flow solver.

Finally, post-processing of the Boeing 747PD model included extraction of forces and moments, surface pressure coefficient plots and some particle traces. The noted speed-up in post-processing is due to improvements in the ability to extract force and moment data and to the smaller grid size which makes the solution easier to view. Overall, the process cycle time for the

second application was reduced by about 50% to approximately 100 days.

The Boeing-developed Aero-Grid-and-Panelling System<sup>20,21</sup> (AGPS) was used to generate the primary surface grids from the CAD definition for the 747PD application, and for subsequent Boeing applications. This step was performed using automated scripts in the AGPS system, and required no more than an hour or two to perform. Thus, in the two baseline configurations, and in subsequent applications, time spent in the manipulation of CAD surfaces was not included in the CFD process time. Thus, here we have defined the beginning of the CFD process as the time at which grid-ready CAD surfaces are available.

### Overset Grid Generation Software

The overset process requires many different software codes: SURGRD<sup>22</sup> and WINGCAP for performing surface grid generation, HYPGEN<sup>23</sup> and LEGRID<sup>24</sup> for the volume grid generation, SMOGRD for smoothing of volume grids, PROGRD<sup>25</sup> for surface-to-surface projections, PEGSUS<sup>26</sup> for performing the joining of the individual overset volume grids, MIXSUR<sup>27,28</sup> for generating a unique, air-tight force integration surface, and OVERFLOW for computing the flow field. In addition, several other codes are used to post-process the solution: PLOT3D<sup>29</sup> for general purpose plotting of grids and solutions; MINTERP for extracting surface pressure coefficient data at specified planes; and VPRO for extracting velocity profiles along specified lines. Details of the use of some of these codes are found in Rogers *et al.*<sup>9</sup> All of these tools, except PEGSUS, OVERFLOW, and PLOT3D, are contained in a software package known as the Chimera Grid Tools (CGT).<sup>30</sup>

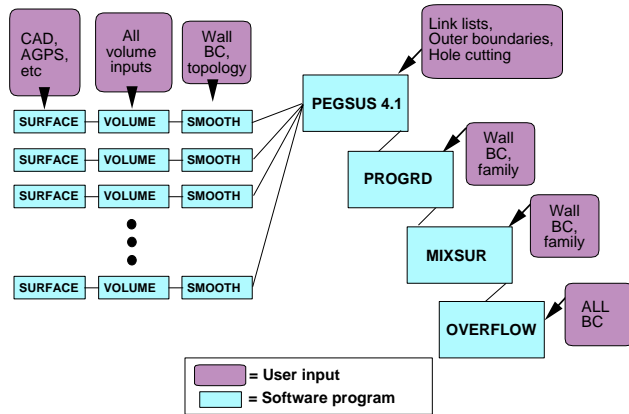
A typical application of this process required the user to provide separate input files for each of these codes, all generated manually. Many of these input files contained the same or similar information, such as a definition of the grid indices for the no-slip walls. For large, complex problems with many zones, this process was very tedious, and prone to errors. An error that was introduced early in the process may not be caught until much later, such as during the running of the flow solver. This can lead to significant delays, unnecessary repetition of the process, and inaccurate results. Thus, there was a need for new software capable of automating the generation of these input files.

### New Script System

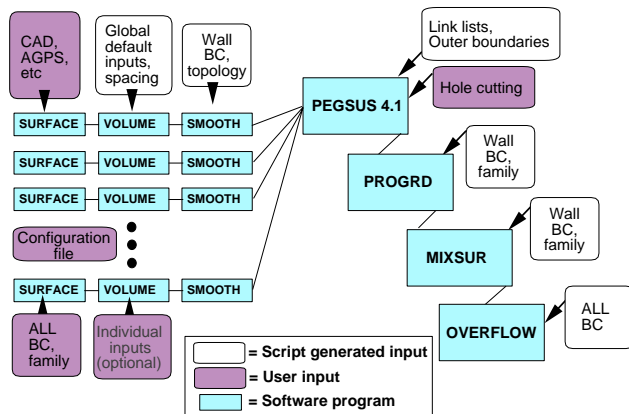
In order to meet the 50-day and 5-day goals, a number of improvements to the CFD process, and more specifically, to the grid-generation process, had to be made. To reduce the amount of manual work required by the user, a series of software scripts were developed and tested before initiating the work on the Boeing

777 CFD analysis. Recognizing that most of the information required by these codes is contained in the boundary-condition (BC) input to the flow solver, it was decided to require that the user supply this BC information for each zone at the beginning of the process. The new scripts control the process once the user has built the surface grids for most of the zones, and provided their boundary conditions. The user also supplies two additional input files: **a configuration file** containing a list of the root-names of each grid to be included in the configuration; and **an input file** which defines default values for a number of input variables, as well as grid-specific values when the user wishes to override the default values.

Given the surface grids, BCs, and these two input files, the script system contains tools which build all of the volume grids, performs elliptic smoothing where needed on these grids, and builds input files for the MIXSUR, PROGRD, PLOT3D, and OVERFLOW programs, as well as part of the input for the PEGSUS program. Figures 2a and 2b show schematic diagrams of the old and new CFD processes, respectively.



a) Old process



b) New process

Fig. 2 Schematic diagrams of grid processes.

The scripted generation of the various input files greatly reduces the chances of user input errors, and

in practice has been found to dramatically speed up the process of building a complete grid system. In addition, the use of a global configuration-definition file allows the user to change the computational configuration quickly and easily by adding and/or subtracting different grids or components within this file.

The script system also defines a series of file suffixes that describe the specific contents of the files used in the gridding process. This provides a built-in dependence path for each file in the process. The scripts utilize this and are capable of updating the entire grid system automatically when a single input is changed, and does so by performing updates of only the files which are dependent on the modified input. In addition, the scripts have the ability to parse what is known as “family” information from the boundary condition files if the user desires. A family is a grouping of individual surfaces which comprise an entire component. The input consists of identifying a family name for each wall boundary condition. This information is used in the projection process by the PROGRD software, and in the force and moment integration (MIXSUR) process, so that forces acting on individual components, as well as the total force, are automatically computed. All of the process-improvement software developed in the current work, including the new script system, has been incorporated into the CGT version 1.1, released in November 1999.

### Boeing 777-200 CFD Model

The 777 computations simulate the 4.2%-scale, full-span model of the Boeing 777-200 aircraft as tested in the NASA Ames 12-Foot Pressure Wind Tunnel. A photograph of this model is shown in Fig. 3. The major aircraft components included in the computational and experimental models are the fuselage, the main wing, the inboard and outboard leading-edge slats, the Krueger slat, the inboard and outboard flaps, the flap-eron, the engine, the engine strut (also known as the pylon), and the vertical tail, as listed in Table 1.



Fig. 3 Boeing 777-200 wind-tunnel model.

The primary surface grids for the 777 were generated using AGPS at Boeing. Additional surface grids, such as wingcap grids and collar grids were generated using the tools in the CGT package. The rest of the process relied on the new scripting system. After running AGPS, the entire grid-system for the 777 was generated on an SGI Octane workstation, with two R10000 195 MHz processors, 896MB of memory, and 13GB of disk space. The resulting grid system for the Boeing 777-200 aircraft configured for landing consists of 22.4 million grid points within 79 overset zones. A view of all of the surface grids is shown in Fig. 4, and a view of the surface grids on the flaps and inboard fairing is shown in Fig. 5. Figure 4 shows only every fourth grid point in each direction, whereas Fig. 5 includes all the surface grid points.



Fig. 4 Surface grids on Boeing 777-200.

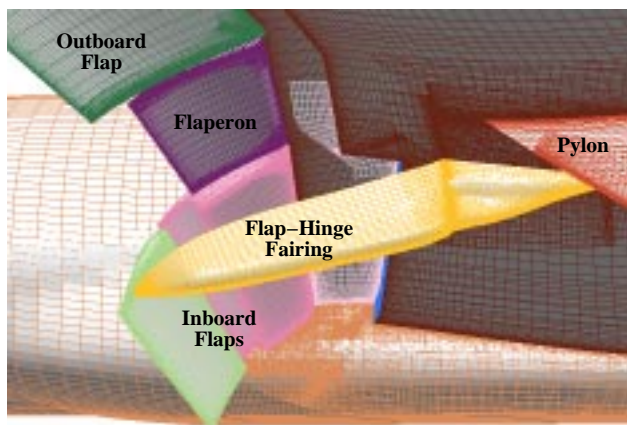


Fig. 5 Surface grids on flaps and inboard fairing.

An attempt was made to generate grids that would be adequate for all expected flow features based on experience with previous high-lift CFD problems, mostly involving simulation of two-dimensional multi-element airfoils. Grid spacing of  $10^{-6}$  times the aerodynamic chord was applied normal to the surface. Also, the maximum grid-stretching ratio in the normal direction

was limited to 1.25. A total of 5617 orphan points (approximately 0.02% of the total points) remained within the grid system after the overset process; averaging is used to update these points within the OVERFLOW code. An orphan point is a boundary point requiring interpolated solution data from a neighboring grid, but for which the software cannot find a neighbor grid with adequate overlap.

### 777 Computation

All of the OVERFLOW computations in the current work utilized the third-order upwind-differencing method of Roe,<sup>31</sup> and the Spalart-Allmaras turbulence model,<sup>32</sup> with the flow assumed to be fully-turbulent. The viscous terms were computed in all three computational directions, however the cross-derivative viscous terms were not included. These were not used because they add about 10% to the cost of the computation, and because previous test cases have shown that their use does not affect the solution. The multi-grid option<sup>17</sup> to the code was used with three levels.

The simulation conditions for the current analysis corresponded to data acquired during wind-tunnel Run 421 in the NASA Ames 12-Foot Pressure Wind Tunnel. The model was configured for landing as defined by the Flaps-30 setting. The flow had a free-stream Mach number of 0.2, a total pressure of 4.5 atmospheres and a Reynolds number based on the mean aerodynamic chord of 5.8 million. The initial simulation was performed at 8 degrees angle of attack. The simulation was conducted in free-air; no wind-tunnel mounting hardware was modeled. The experimental data used for the comparisons was corrected for wind tunnel wall and blockage interference, but excludes tare and interference corrections for the bi-pod mounting device. The magnitude of tare and interference corrections to the wind tunnel data was estimated to be less than 1%. The initial case converged in 2180 multi-grid cycles, and required 201 Cray C90 hours. The computed lift and drag were in excellent agreement with the experimental values: the total lift coefficient was 1.2% lower than experiment, and the total drag coefficient was 2.6% lower than experiment. See the companion paper by Rogers *et al.*<sup>33</sup> for a detailed presentation of the computed results for this configuration, including results for seven different angles of attack, comparison of surface pressure coefficients, and a study of the effect of certain geometry changes.

### 777 CFD Process Time

The entire 777 analysis process began on August 3rd, 1998, and the converged flow solution for the complete configuration was post-processed on October 2nd, which was 45 business days after the start

of the process. However, the first converged solution, which did not include the flap fairings, was obtained on September 14th (30 business days). The CAD definition for the fairings could not be obtained until mid-way through the analysis process. Seven different people contributed to parts of the grid-generation process, most of them on a part-time basis, working only a few days each. The total labor time spent on the process was 384 labor hours, or 48 labor days.

The time spent performing the entire CFD analysis of the 777 was recorded by each team member each day of the project, and their time was categorized by the type of activity they performed. Table 2 shows the time spent generating grids for each aircraft major part: wing and body, leading-edge (LE) devices, trailing-edge (TE) devices, engine, engine strut, and vertical tail. For each aircraft component, time is listed for surface grids (i.e. AGPS or CGT package), volume grids (i.e. HYPGEN or LEGRID), and over-setting (i.e. PEGSUS or PROGRD).

**Table 2 Grid Generation Time, Hours**

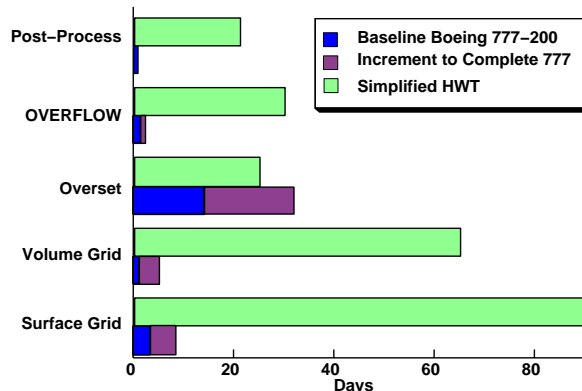
Aircraft Part	Surface Grid	Volume Grid	Overset	Total
Wing-Body	34.5	2.5	32.5	69.5
LE Devices	0.5	0.5	52.0	53.0
TE Devices	21.0	10.0	93.5	124.5
Engine	0.5	0.5	6.0	7.0
Strut	4.0	26.0	67.5	97.5
Vert. Tail	5.0	1.5	4.0	10.5
Total	65.6	41.0	255.5	362.0

The 201 Cray C90 CPU hours required for the first computed case was run using 15 multi-task queue submissions on the NASA Ames 16-processor Cray C90 known as “vonneumann.” Each job submission took approximately 2.25 wall clock hours to execute for a total of 33.75 wall clock hours of running time. The average concurrency attained for these jobs was about 7.0 on this 16-processor computer. These jobs were all run during a 5 day period, although it is noted that the machine was unavailable for a day and a half during this time due to system maintenance. The wall-clock time that is required to complete the CFD process is not the best indicator of improvements to the flow solver, due to the variability in computer resource demands on a non-dedicated system. This variability is particularly a factor during the 50-day activity because the NASA Cray was heavily loaded during this project, which was during the end of the computer accounting year.

#### Identification of Process Improvements

The geometry of the 1996 benchmark model, the simplified HWT, was described in the Introduction,

and in Table 1. The complete CFD model of the Boeing 777-200 has significantly more geometric complexity than the simplified HWT. In order to compare modeling of geometrically similar vehicles, the process time for the Boeing 777-200 configuration excluding the engine strut, main wing leading-edge steps and flap fairings was identified. The process time for this configuration, referred to here as the baseline 777 geometry, is compared with the process time for the benchmark simplified HWT simulation in Fig. 6. The figure also includes the increment of time required for analysis of the complete 777 model.



**Fig. 6 Comparison of process time for the baseline 777 and the simplified HWT.**

The total time to perform the CFD analysis has decreased by one order of magnitude since 1996: the simplified HWT required 231 days, the baseline 777 required 21 days. The largest improvements are in the areas of surface- and volume-grid generation. One of the major contributors to surface grid time reductions is the evolution of standardized grid topologies for high-lift system components. The volume grid generation has been improved through better versions of the HYPGEN and LEGRID programs, and through the use of the scripts. Since the PEGSUS code was used to overset both grid systems, the slight time decrease in the number of days required to overset the baseline 777 mesh reflects user experience with the code, and improved turn-around time on fast workstations. The time reduction shown for the OVERFLOW simulation is due the use of the new scripting software, which produced error-free input files, and better quality grids. The improved quality includes more extensive use of double-fringe overlap between neighboring grids, proper smoothing of the volume grids to remove fine spacing at off-body grid surfaces, and no grids with negative cell volumes. The current computations ran to convergence without any user intervention once the job was initiated. During the HWT runs in 1996, there were many user interventions to adjust inputs and modify the grid system during the running of the flow solver to correct errors. Finally, during the past two years, post-processing tools were developed to en-

able the delivery of forces and moments and pressure data nearly simultaneously with the completion of the flow solver.

In Fig. 7, the process time for the Boeing 777-200 application is analyzed for four build-up configurations. These configurations begin with the baseline high-lift vehicle which is defined to include all components except the engine strut, the leading-edge steps and the flap fairings. Adding the strut to the baseline vehicle required 11 days for a cumulative total of 32 days. Adding the leading-edge steps on the main wing to the model of the basic vehicle with strut required 6 days. Finally, incorporating the flap fairings into the simulation resulted in a total of 48 days to simulate the complete configuration. Figure 1 included the target times that were estimated prior to the project start for completing each phase of the CFD process. Only the surface-grid generation time exceeded the target by more than one day. It is now clear that for a single-point analysis, the most labor-intensive phase of the simulation is over-setting the grid system; therefore, future development efforts must reduce the effort for this task. However, if many analysis runs are to be computed, the wall-clock time waiting for OVERFLOW to run will be the largest increment in the CFD cycle.

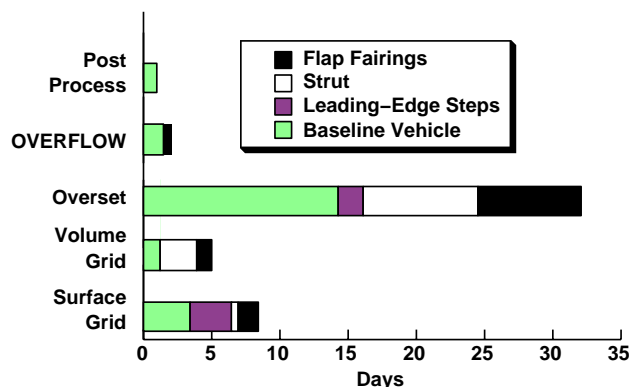


Fig. 7 Process time for geometric subsets of the 777 model.

In Figs. 6 and 7 and Table 1, it is seen that the overset process requires 70.5% of the grid-generation time. Surface and volume gridding require 18.4% and 11.1%, respectively. The surface grid generation time is large for the wing-body and is mostly due to grids for the leading-edge steps. Also, several iterations were required to develop engine strut grids that produced acceptable volume grids to interface with the leading-edge devices. Most of the time spent on the leading-edge devices was used to overset the grids, and 50% of this total time was spent on the Krueger element. Each of these three regions has geometric features that were not present on high-lift configurations modeled previously.

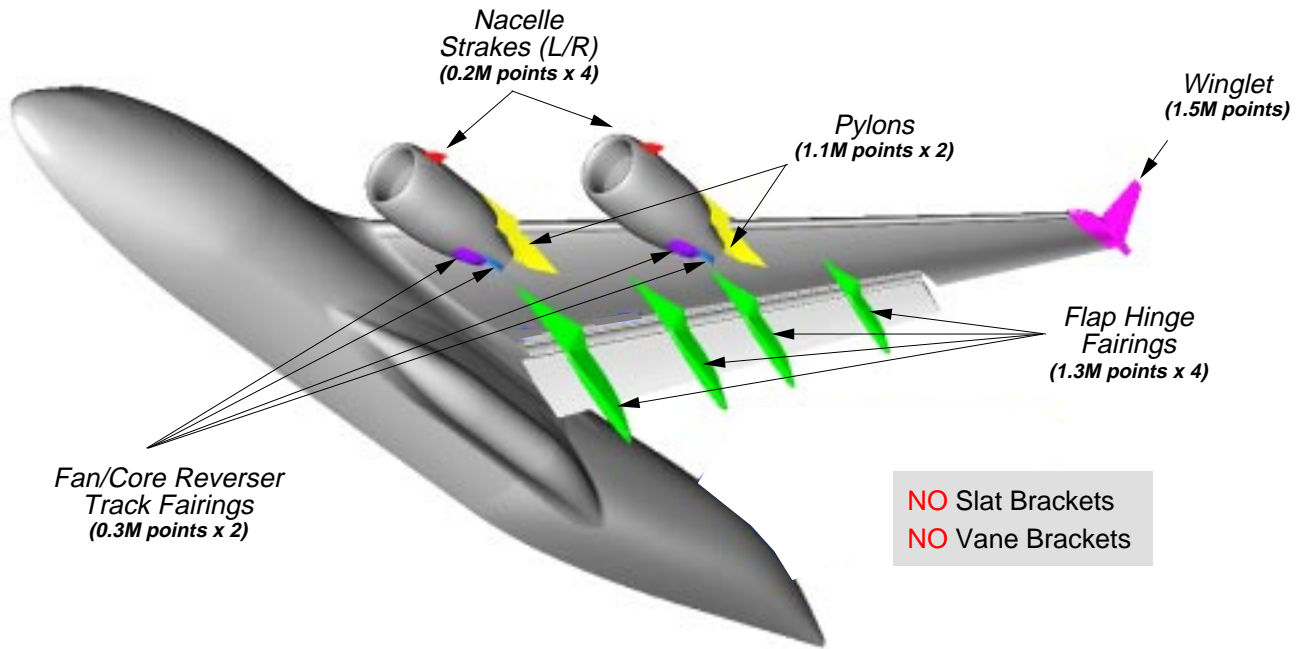
## Boeing 777 Flap Configuration Change

As discussed in previous sections, one goal of the current work is to develop the capability to perform trade studies of geometric changes in a matter of days. The ability to do this was demonstrated for the complete 777 CFD model utilizing the script system developed for the initial 50-day analysis. An alternate design of the outboard flap was generated in CAD. Using this as a starting point, new surface and volume grids were generated. Because of additional camber and a different flap deflection, the grids for the two outboard flap fairings had to be modified to accommodate this flap. New surface and volume grids were generated for the new flap and fairings within a few hours. Within two days, a new grid system was completed and ready to run in OVERFLOW. A converged solution for the alternate flap required 250 Cray C90 hours, which required only 48 wall-clock hours as the system was under utilized at the time. Thus, within 4 calendar days, and utilizing 16 labor hours, a post-processed solution (including forces, moments, and surface pressure coefficient data extracted at pressure tap rows) was generated.

## High-Wing Transport CFD Model

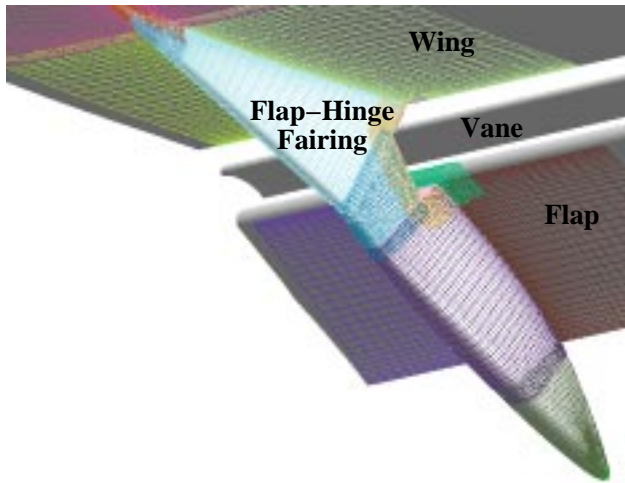
Subsequent to the 777 work, the new scripts were applied to the problem of generating several new grid systems for the complete HWT aircraft. Although a complete grid system had already been generated for the this aircraft, it was desired to take advantage of the new scripts because a number of different geometry changes were to be studied computationally. In fact, plans called for computations of many cases with a long list of possible configuration variables: use of either a vane-flap, or two different single-slotted flaps, all at different flap and spoiler deflections; with or without the pylon and nacelle, with or without the winglet; with or without the engine chines; and all utilizing either free-air boundaries or a computational model of the test-section of the NASA Ames 12-Foot Pressure Wind Tunnel.

Figure 8 shows the HWT baseline geometry configured for landing. The parts which are highlighted in the figure include the flap-hinge fairings (which are sealed against both the wing and the flap), the winglet, the pylons, the nacelle strakes, and the fan and core reverser-track fairings. No slat brackets or vane brackets are included in the computational geometry. Figure 9 shows a view of the surface grids on one of the flap-hinge fairings. Figure 10 shows the grids in the symmetry plane of one of the nacelles. The baseline grid system for this configuration consists of 35.1 million grid points, and 153 grid zones.



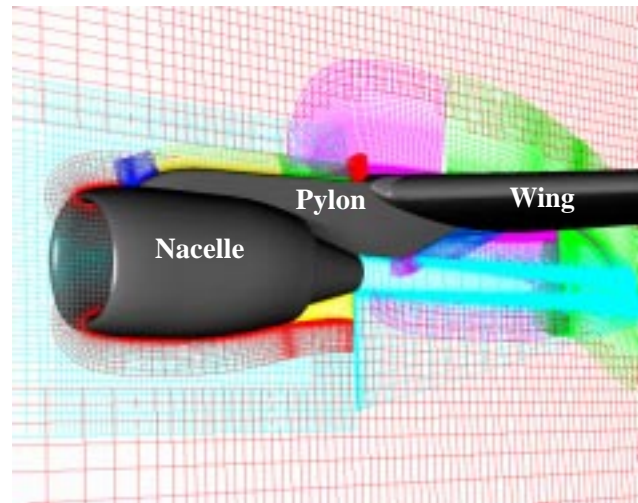
**Fig. 8 HWT geometry**

geometry. Scripts have been written to automatically generate these surface grids for different deflections angles of the vane, flap, and spoiler.



**Fig. 9 HWT flap-hinge fairing surface grids.**

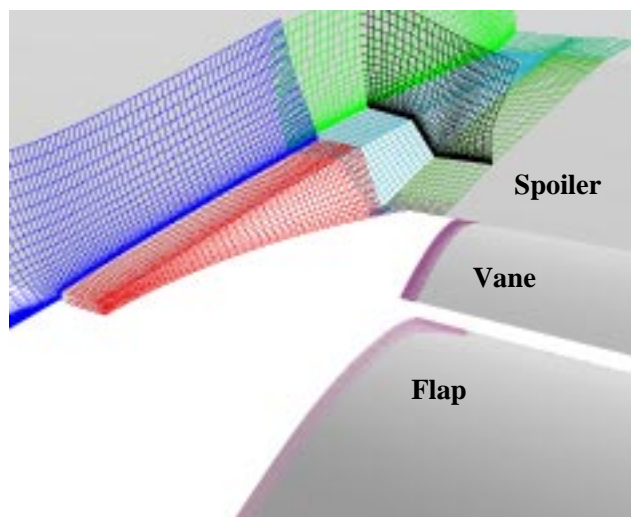
The previous HWT grid system was modified to take advantage of the new scripts. The ability to control the geometry through the use of the configuration input file was utilized in this instance. A number of script variables were created which controlled the geometric configuration. Since the script system requires the surface grids as a starting point, a series of custom programs and scripts were created which are capable of generating the appropriate surface grids for the given configuration. The grids for any combination of these configuration variables could then be generated by changing the values of these inputs and running the scripts. Figure 11 shows some of the grids at the outboard end of the vane and flap, as well as the deflection of the spoiler and the edge of the flap-cove. A number of cap grids are used to cover this region of the



**Fig. 10 HWT pylon and nacelle grids.**

Although the ability to generate grids for all the above possible combinations is not completely automated, it is nearly so. The user still needs to supply inputs to the PEGSUS code to perform the hole-cutting. All other input files are generated automatically. With the use of phantom hole-cutting techniques for high-lift elements,<sup>9</sup> the hole-cutting process can be performed in a matter of days for larger changes (such as a new flap), and less than a day of labor time for small changes. In practice, this script system has been used to generate over a dozen different grid systems for various different HWT configurations, each requiring from one to five days to complete. Given the amount of input required to analyze configurations requiring over

30 million grid points and over 150 zones, this is a significant improvement over the capability of only two years ago.



**Fig. 11 HWT wing cove caps and flap caps.**

These HWT grid systems have been utilized to run over 30 different computations both with and without engine power. The lift-coefficients of the power-off computations agree very well with experimental lift values for a large range of angle of attack, up to and including maximum lift. The power-on cases, however, show significant differences compared to the experimental results for most angles of attack. Details of these computations and the comparison with experiment can be found in the companion paper by Slotnick *et al.*<sup>34</sup>

### Summary and Conclusion

The AST/IWD High-Lift CFD Team successfully reduced the cycle time for a Navier-Stokes simulation of a complete subsonic transport configured for high lift by one order of magnitude compared with the 1996 benchmark. The first solution of the baseline Boeing 777-200 aircraft configured for landing was obtained in 21 labor days. The complete aircraft was analyzed within 48 labor days. The simulations used the OVERFLOW code with structured, overset grids and the Spalart-Allmaras turbulence model. The development and application of the automated OVERSET script system that streamlines the overset grid generation process is the primary reason for the reduction in cycle time. The scripts eliminate manual inputs that were often duplicative and error prone. Also, new post-processing tools enable the delivery of engineering data nearly simultaneously with the completion of the flow solver runs. For single-point analysis, over-setting the grid system, which accounts for 71% of the grid generation effort, is now the most labor-intensive task within the computational process. However, for multi-point analyses requiring many flow solver runs, the solution

turn-around time is the most time-consuming part of the CFD cycle.

For design trade studies testing various hardware configurations, modifications to the grid system are required. For variations to a baseline geometry, such as a change in flap rigging, the overset scripts facilitate changes and enable configuration management of the grid systems. This has been demonstrated for both the HWT high-lift landing configuration and the Boeing 777-200 landing configuration, where solutions for alternate flap designs have been performed in a matter of days.

The new scripts were written to be general purpose, with no assumption about the vehicle being analyzed. Subsequent to the current work, these scripts have been applied to many other CFD analysis problems, from aeronautics, space, and marine applications. They are proving to be very useful tools over a wide range of applications.

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